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Removing Roll and Heave Artifacts from High-Resolution Multibeam Bathymetric Data

Anna M. Crawford

Defence R&D Canada

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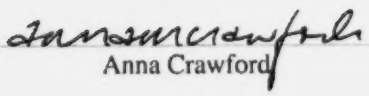

Anna Crawford

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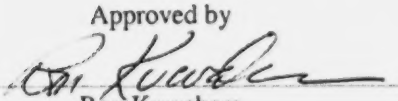

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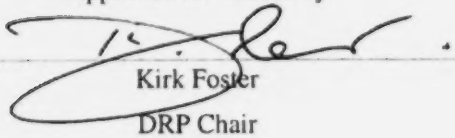

Kirk Foster

DRP Chair

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Abstract

DRDC Atlantic recently acquired a Reson 8125 bathymetric sonar. This is a very high resolution multibeam sonar that requires accurate measurement of the instantaneous attitude and position of the vessel in order to properly determine seabed bathymetry. During early deployments of the instrument, roll and heave contamination of the bathymetric data resulted from less–than optimal configuration of the system ancillary sensors. In addition, the data show evidence of unresolved motions, mainly flex in the sonar mounting pole.

In the absence of commercial software tools to deal with this problem, a method has been developed for removing some of these artifacts from the data. It is primarily intended for use in salvaging useful information from the early data sets now that the Reson system setup has subsequently been improved, however it is likely that pole flexure will continue to be an issue when deploying this sonar on CFAV Quest. The algorithm has been implemented in Matlab (The Mathworks, Inc.), and a student, David Cowan, has written a version for IDL (Research Systems, Inc.).

Résumé

RDDC Atlantique a récemment fait l'acquisition d'un sonar bathymétrique Reson 8125. Il s'agit d'un sonar multi-faisceaux à très haute résolution exigeant la mesure précise de l'assiette et de la position instantanées du navire pour les levés bathymétriques des fonds marins. Dans les premières applications de l'instrument, la contamination des données bathymétriques par roulis et levée était due à la configuration moins qu'optimale des capteurs auxiliaires du système. De plus, les données révèlent la présence de mouvements non résolus, principalement le fléchissement du poteau servant au montage du sonar.

En l'absence sur le marché de logiciels permettant de résoudre ce problème, on a mis au point une méthode en vue de supprimer certains de ces artéfacts des données. Cette méthode vise principalement à sauvegarder l'information utile des premiers ensembles de données, maintenant que l'installation du système Reson a été améliorée, mais il est probable que le fléchissement du poteau continue de faire problème une fois que ce sonar sera monté à bord du NAFC Quest. L'algorithme a été mis en application chez Matlab (The Mathworks, Inc.), et un étudiant, David Cowan, en a préparé une version pour IDL (Research Systems, Inc.).

Executive summary

Introduction
High resolution bathymetric sonars have direct application in the area of mine detection by high frequency sonars and for other naval applications which require high accuracy and resolution in imaging of the seabed and underwater objects. When DRDC Atlantic first acquired a Reson 8125 multibeam bathymetric sonar, there were some configuration issues which led to contamination of the collected bathymetry data by roll, heave and other ship motion artifacts. A method has been developed that removes some of these so that useful information can be derived from those early data sets. DRDC Atlantic does not possess commercial software that can do this, though such tools probably are available.

Significance of Results
After applying the cleaning method to data sets collected on the Scotian Shelf (Q267) and over mine–shaped targets in Esquimalt, smaller scale features are resolvable in the bathymetry data that would otherwise be masked by the artifacts.

Future Plans
Most of the deployment issues which compromised the earlier bathymetry measurements with the Reson system have been resolved, however, artifacts due to unmeasured motions (mainly flex in the mounting pole) may continue to be present. This data cleaning method is applicable to the components of pole motion that appear as roll and heave, and so may continue to be useful for cleaning data collected with the multibeam sonar in the future.

Crawford, Anna M. 2003. Removing Roll and Heave Artifacts from High–Resolution Multibeam Bathymetric Data. TM2003–243. DRDC Atlantic.

Sommaire

Introduction
Les sonars bathymétriques à haute résolution ont une application directe dans le domaine de la détection des mines par des sonars à hautes fréquences ainsi que dans dautres applications navales qui requiàrent une précision et une résolution extrêmes dans limagerie des fonds marins et des objets sous-marins. Lorsque RDDC Atlantique a fait l'acquisition d'un sonar bathymétrique multi-faisceaux Reson 8125, il existait divers problèmes de configuration occasionnant la contamination des données bathymétriques par des artéfacts de roulis, de levée et d'autres mouvements du navire. On a mis au point une méthode en vue de supprimer certains de ces artéfacts pour que l'information utile puisse être extraite de ces ensembles de données. RDDC Atlantique ne possède pas de logiciel disponible sur le marché qui puisse le faire, bien qu'il en existe probablement.

Signification des résultats
Après l'application de la méthode d'épuration aux ensembles de données recueillis sur le Plateau néo-écossais (Q267) et sur des cibles en forme de mines à Esquimalt, il est possible d'effectuer la résolution d'éléments à échelle inférieure dans les données bathymétriques, qui seraient autrement masqués par les artéfacts.

Plans futurs
La plupart des problèmes d'application qui compromettaient les premières mesures bathymétriques effectuées au moyen du système Reson ont été résolus, mais il se pourrait que des artéfacts dus à des mouvements non mesurés (principalement le fléchissement du poteau de montage) demeurent toujours présents. Cette technique d'´puration des données s'applique aux composantes de mouvement du poteau qui apparaissent comme du roulis et de la levée et pourrait donc s'avérer utile pour l'épuration des données recueillies dans l'avenir au moyen du sonar multi-faisceaux.

Crawford, Anna M. 2003. Suppression des artéfacts de roulis et de levée des données bathymétriques multi-faisceaux à haute résolution. TM2003–243. RDDC Atlantique.

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1 Introduction

A fully operational multibeam sonar system incorporates a large number of complicated sub–systems and ancillary sensors, all of which need to be understood and properly set up for accuracy of the resulting bathymetry measurements. DRDC Atlantic recently acquired a Reson 8125 multibeam sonar which is a fine example of such a complicated system. The ancillary sensor suite consists of a heading sensor (gyro), a Motion Reference Unit (MRU), a sound velocity probe (SVP) and a Differential Global Positioning System receiver (DGPS). During the first few months of operations with this new sonar, some of these sensors were not properly configured or were not communicating with each other. The result of this was contamination of the collected bathymetry data with artifacts of the ship motion (mostly roll and heave). In addition, the data shows evidence of motion of the sonar head relative to the ship due to flex in the sonar mounting pole, which is not measured by the motion sensor.

Over the course of several operations subsequent to the initial deployments of the system, problems with the configuration have been eliminated one by one so that currently the system is approaching an optimal operating state. A remaining factor which cannot be easily remedied is the flex of the mounting pole.

Though the future of operations with this high–resolution instrument promise exciting science, we are left with survey data from the early history of its use that contain motion contamination. DRDC Atlantic does not currently have commercial software tools that can deal with this problem, however a method has been devised for removing the roll and heave components of these artifacts. This was developed and written in Matlab (The Mathworks, Inc.), and has also subsequently been implemented by a student, David Cowan, in IDL (Research Systems, Inc.). This method has allowed extraction of some interesting smaller scale bathymetric features from the motion-contaminated data sets.

2 Multibeam Geometry Considerations

A multibeam sonar system measures bathymetry by sensing the range to the seabed along each beam, then knowing the angles of the beams and the attitude and position of the sonar head, determines the positions of the beam footprints on the seabed. The Reson 8125 has 240 half–degree beams arranged in a fan shaped wedge, with the outermost beams at $\pm 60°$ from vertical to either side of the sonar nadir (athwartships) and a $1°$ fore–aft beamwidth. As the vessel travels forward, a swath along the seafloor is mapped which has width determined by the water depth. For each sonar ping, determining where each of the 240 beams intersect seabed requires accurate knowledge of the attitude, position and heading of the sonar head at the time of that ping. Furthermore, accuracy is required in measurement of the relative positions of the sonar head, the ship motion sensor, and the center of gravity (CoG) of the vessel since these are not co–located. Rotations and translations of the vessel are assumed to act about the CoG, but are measured at the locations of the MRU and GPS receiver antenna, and the resulting motion of the sonar head is then calculated using geometry. Figure 1 illustrates a 3–dimensional view of a vessel carrying a multibeam system, including the sonar head, some ancillary sensors and the CoG of the vessel.

For future reference, a *line* refers to the set of seabed positions derived from one transmitted ping over all beams (240 of them for the Reson system). Each line then contains a bathymetric profile generally running perpendicular to the alongtrack direction (the ship heading). A series of lines is compiled as a swath.

There are a number of ways that inaccuracy can introduce motion artifacts or other errors into bathymetry data.

- **Inaccurate CoG or Sensor Offsets:** If any of the relative positions of the sonar head, CoG, GPS receiver and MRU are incorrectly determined, then the geometric calculation of the motion and position of the sonar head from the measured attitude and position will give incorrect results.

- **Sensor Latency:** There is a time delay between measurement of ship attitude by the MRU, or of ship position by the GPS, and reporting of this information to the sonar processing software. This can result in previous motion or position measurements being applied to the current sonar ping ranges while the attitude and/or position has likely changed in the meantime.

- **Miscommunication Between Sensors:** In order to operate optimally, some system sensors require aiding information from others. The MRU in particular needs to be in communication with the heading sensor (gyro) so that centrifugal acceleration is not confused with other motions.

- **Sound Speed Profile:** The sonar head has a co–located sound speed probe, the output of which aids in beamforming. If the sound speed in the surrounding

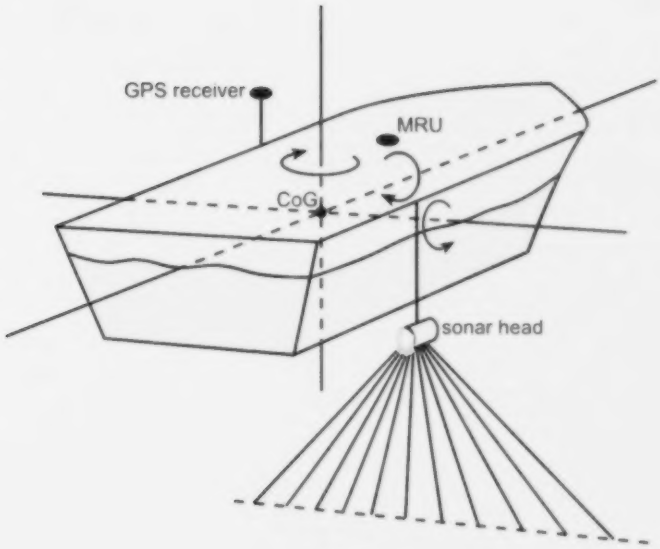

Figure 1: *3–dimensional view of a vessel–mounted multibeam system. Rotation and translation of the vessel are about the CoG. Position is measured at the GPS receiver and attitude, at the MRU.*

water column differs from that at the point of measurement or from that assumed by the processing software, the difference between real and calculated acoustic refraction results in erroneous positioning of the beam footprints on the seabed.

- **Unresolved Motions:** If there is relative motion between the attitude or position sensors and the sonar head, this is not measured and therefore will not be included in the beam footprint position calculations. As previously mentioned, an example of this is flex in the sonar mounting pole.

There are other more subtle causes which tie into one or more of the above factors. For example, the motion sensor uses Kalman filtering to condition the attitude output. In addition to needing the aiding gyro information, it also requires filter settings that are appropriate to the operating environment. Motion in Very long swell waves may not be properly resolved when operating with the settings appropriate for short sea waves.

In more recent deployments, the latency and sensor miscommunication issues have been resolved. The sonar processor can utilize a Pulse Per Second (PPS) time tag output from the GPS to attach the correct attitude and position measurements to the appropriate set of ping beam footprints. This eliminates the latency problem. In addition, the serial communications between the gyro, motion sensor and sonar processor have now been correctly configured.

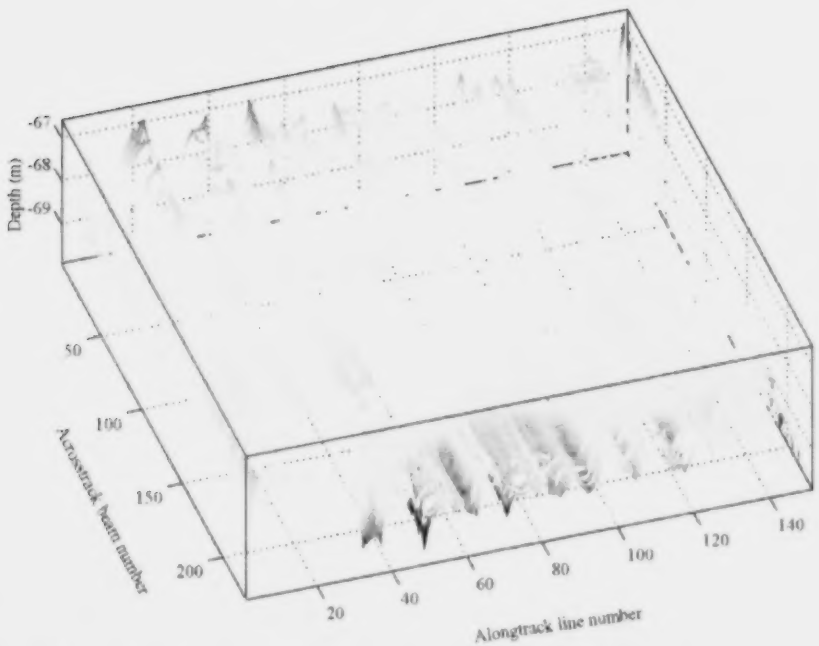

Figure 2: *An example of roll and heave contaminated bathymetry data. The mean water depth is 68 meters.*

The artifacts evident in the bathymetry data collected during the first few deployments of the DRDC Atlantic Reson 8125 are mainly due to a combination of three of the above–listed factors — sensor latency, miscommunication between sensors and unresolved motion. These show primarily as what will be referred to as *roll* and *heave* artifacts, though would more properly be called *roll–like* and *heave–like*. Roll artifacts are characterized by vertical deviations that increase in amplitude toward the outer beams. These are equivalent to rotation of the ship about a fore–aft axis, with deviation of opposite sign on opposite sides of center. Heave artifacts are equivalent to vertical motions of the ship and have a constant value along lines. Both types of artifacts can be recognized by the alongtrack oscillations they induce.

Figure 2 illustrates an example of motion–contaminated data, mostly suffering from roll artifacts. The outer beams show deviations of up to a meter in 68 meter water depth. There is a lesser degree of heave contamination in this particular example. This data was collected during cruise Q267 aboard CFAV Quest on the Scotian Shelf while waves were running 3–4 meters high. Beam footprint positions that have been rejected by the sonar processor automatic quality control algorithms leave holes (white spaces) in the surface in the image.

3 The Roll and Heave Cleaning Method

The algorithm for removing roll and heave contamination proceeds as follows:

- The sonar processing software exports the calculated positions of the beam footprints (X, Y, Z values), along with line and beam numbers, in a formatted ASCII file. The position of the sonar head and attitude information that accompany each ping is output in a header with each line of beam footprint coordinates.
- The processing script reads the lines of beam position data and compiles series of slopes and intercepts of least–squares linear regressions to each line, relative to the sonar head position.
- The series of line slopes and intercepts are filtered to remove the high frequency alongtrack variation, leaving the lower frequency (longer length) changes.
- For each line, the slope is adjusted to the filtered slope by rotating about the sonar head position, then the intercept is adjusted to the filtered intercept value by shifting the whole line vertically. All three coordinates of the beam footprint positions for a line are altered by the slope adjustment.
- The adjusted beam footprint positions are output as a new ASCII file with the same format as the original file.

A Matlab implementation of this algorithm is presented in Annex A. It is likely that there are commercially available software packages that use algorithms equivalent to this. The Ocean Mapping Group at University of New Brunswick (John Hughes Clark), for example, has developed tools that work this way.

Figure 3 illustrates the series of line slopes and intercepts that accompany the contaminated data shown in Figure 2. The filtered values are also shown (in red). The adjustments to the intercept are minor, at most about 15 cm. The longer wavelength trends in slope and intercept are retained, since they may represent real bathymetric features. The small scale acrosstrack variations in each line are also retained.

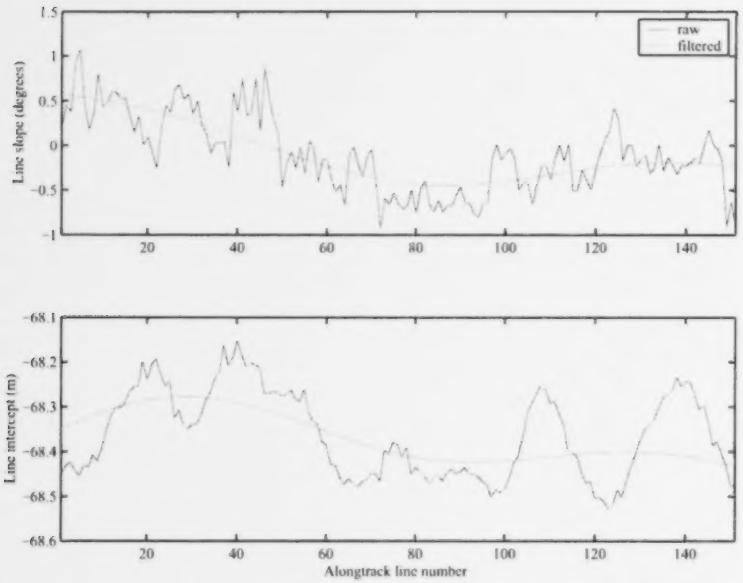

Figure 3: *Raw and filtered line slopes and intercepts for the sample of data shown in Figure 2.*

4 Samples of Cleaned Bathymetric Data

Figure 4 illustrates the output of the cleaning algorithm applied to the data that was shown in Figure 2. Both the original and cleaned data are also shown in plan view in Figure 5.

An interesting small scale feature in the cleaned data shown in Figure 5 are the bedforms in the lower elevation (blue) area to the right in the images. These are ripple bedforms in the coarse sand and gravel sediments found there, with wavelengths about 2 m and heights about 0.1–0.2 m. The boundary between the higher (yellow–green) and lower elevation area is a steep scarp with slope about 30°.

Another example of cleaned bathymetry data is shown in Figure 6. The upper panel shows cleaned and geo-referenced bathymetry data (on a 75 cm by 75 cm grid), while the lower panel shows geo-referenced sidescan sonar data over the same area (20 cm by 20 cm grid). The scour holes surrounding the mine–shaped targets are seen in the bathymetry data in a mean water depth of about 60 meters. A vertical cylinder target just above the center of the images is itself resolved in the bathymetry data.

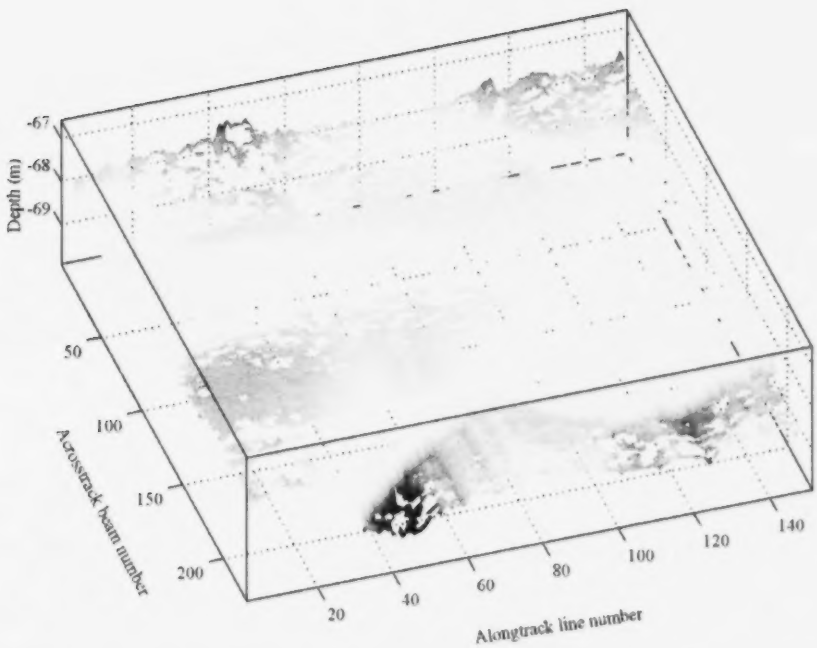

Figure 4: *The results of cleaning the data that was shown in Figure 2.*

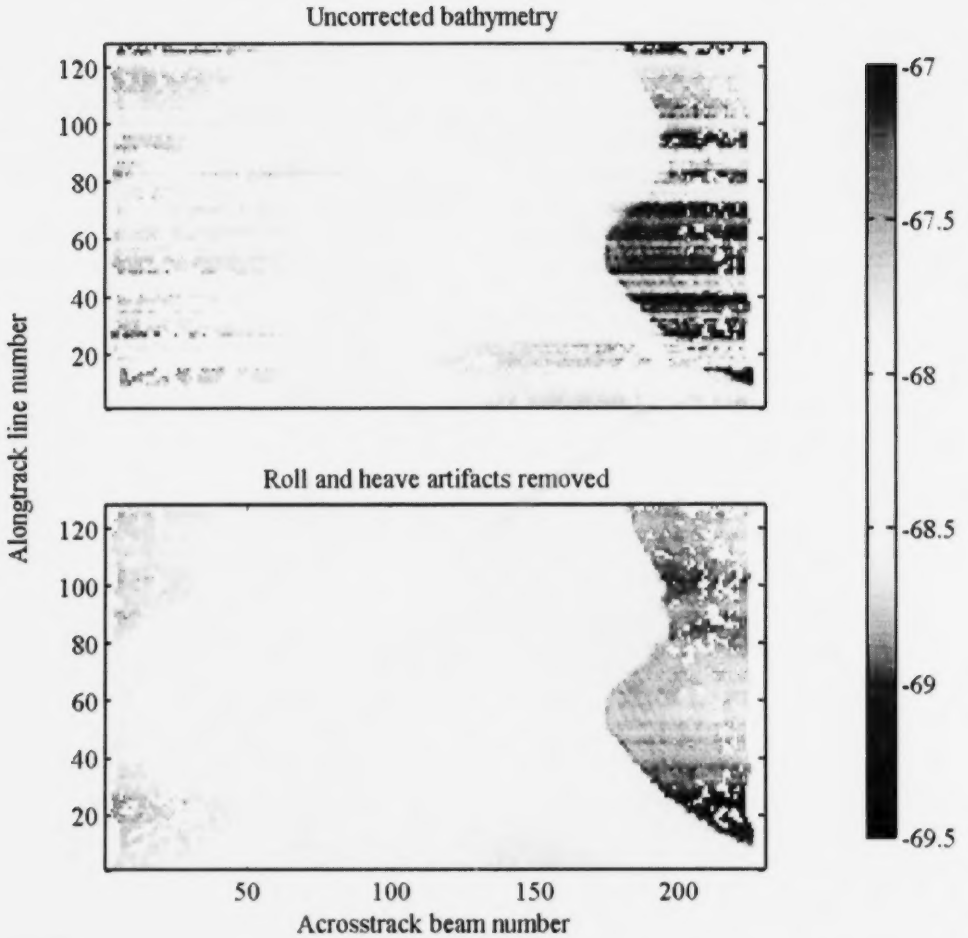

Figure 5: *Plan views of the contaminated and cleaned bathymetry data shown in Figures 2 and 4.*

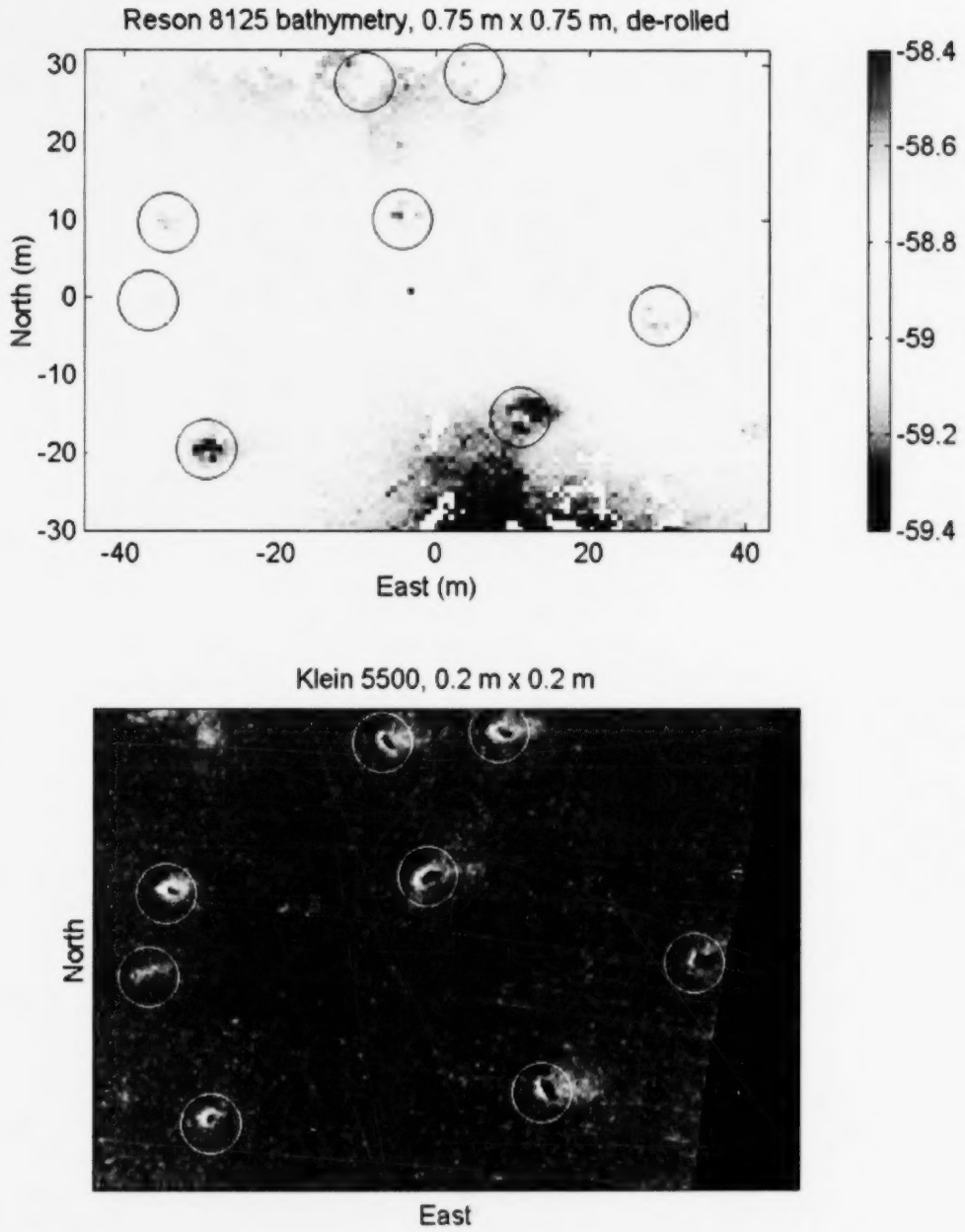

Figure 6: *A cluster of mine–shaped targets in cleaned, geo–referenced bathymetry data and in sidescan sonar data over the same area.*

5 User Beware

Removing the high frequency roll and heave components from a data set may not resolve all the problems. Figures 7 and 8 illustrate an example of data containing other artifacts that cannot be removed by this method. The cleaned data shown in Figure 8 still shows oscillation of the very outer beams after the high frequency variation in line slope has been removed. The residual oscillation has the same frequency as the slope variation that was removed, but is out of phase by 90°. Note that the oscillation of the roll artifact which has been removed has a different peak frequency than the vessel motions (roll, pitch or heave). The residual may be due to refraction effects, as indicated by more strongly affecting the outer beams.

The algorithm as presented (see Annex A) may need to be adjusted to suit the particular situation. At the least, the filtering of the slopes and intercepts should be tuned to the motions evident in the data. As currently implemented, the filters have been specified with window lengths defined by a number of lines, rather than on a time base. This assumes that the sonar ping rate and the frequencies of the unwanted motion contamination do not change significantly over the duration of the set of lines being cleaned. In the case that there are significant measured (real) pitch or roll offset values, the horizontal position of the sonar head may fall some distance away from the center of the line of beam positions on the seabed. Particularly for a large pitch offset, correction by rotation in the vertical plane containing the line will result in distortion of the adjusted line, especially near nadir. Rotation about the sonar head position is in fact only an approximation of the motion being removed from the data. It would be very difficult to determine the true center of rotation from the available information.

Finally, this method is applied to data that is in the form of X, Y, Z values, referenced by line and beam numbers, i.e. data that is in a very raw state. This technique cannot be applied to bathymetric data that has been processed such as by gridding where line and beam numbers (and even ship track and heading) are lost.

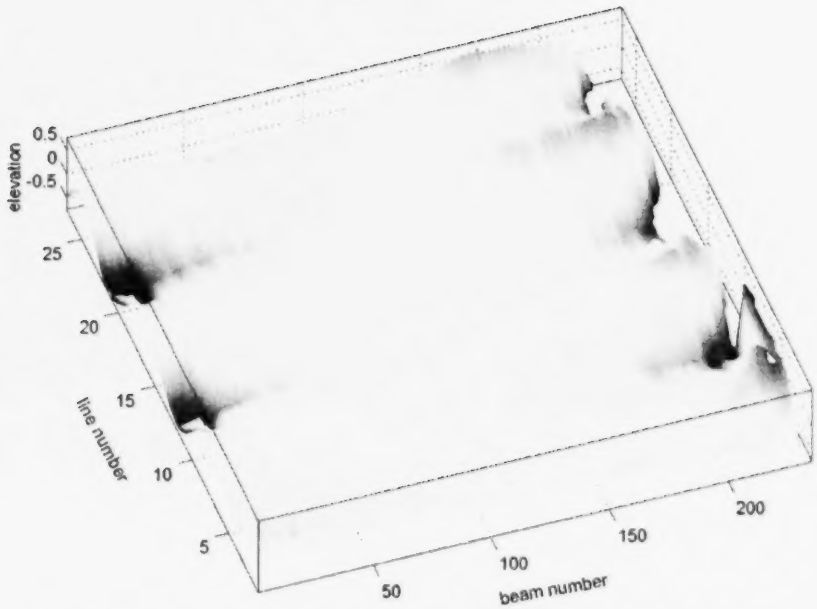

Figure 7: *Raw Reson bathymetry data showing motion contamination.*

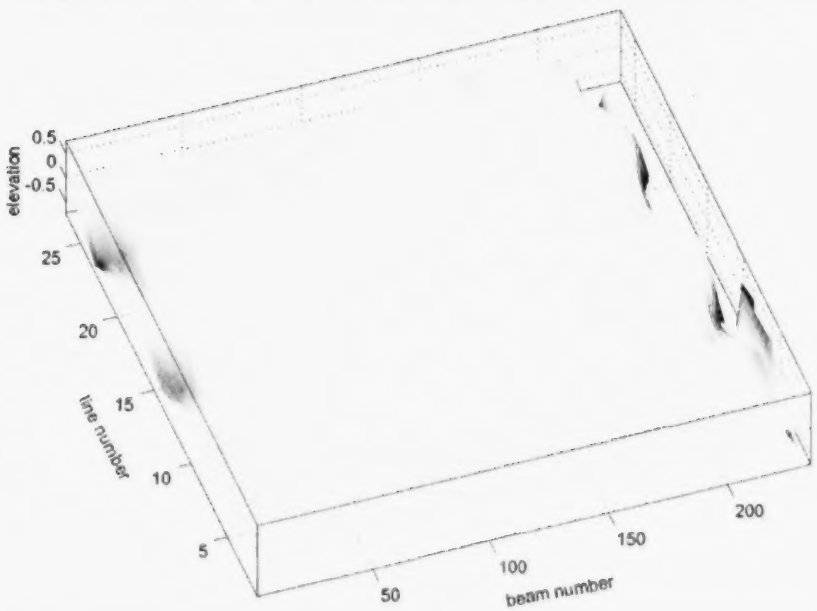

Figure 8: *Results of cleaning the data shown in Figure 7. Note the persistence of alongtrack devation in the outer beams.*

6 Conclusions

The method that has been presented here can be used to remove undesirable motion (roll and heave) contamination from raw multibeam bathymetric data. Some examples have been presented showing the effectiveness of the technique, as well as a few warnings to potential users. The algorithm itself is presented in the Annex.

Application of this technique has allowed some interesting small features to be extracted from bathymetry data that would otherwise be overshadowed by the motion contamination. The Reson 8125 sonar has demonstrated the ability to resolve ripple bedforms of less than half a meter height in almost 70 m water depth in rough seas. The example of the mine-like targets shows promise for the system in future minehunting research.

Annex A: Matlab Implementation of the Algorithm

The Matlab script presented below is not the most computationally efficient method for performing these calculations, but is effective and illustrates the idea.

Starting at the point where the data has already been imported into Matlab variables, the input arrays are `E`, `N`, and `Z`, the 3–dimensional (Easting, Northing, and depth) beam footprint positions with indices [line number, beam number from 1 to 240], and vectors are `refposE`, `refposN` and `refposZ`, the positions of the sonar head for each line. In the arrays `E`, `N` and `Z`, beam positions that have been rejected by the sonar processor quality control algorithms are filled with `NaN` (not a number).

First, the series of line slopes and intercepts, relative to the sonar head, are determined. `R` are the ranges of the beam footprints in a horizontal plane from the horizontal position of the sonar head. Here, `R` is made negative to one side by flagging negative angles, which is appropriate for headings roughly East–West or West–East. In the case of a North–South/South–North heading, `R` would be made negative for `th` greater than +90° or less than -90°. The slope and intercept of a line are then the slope and intercept of the set of values `(R,Z-refposZ)`. The function `find_slope` (presented at the end of the Annex) calculates a linear least–squares regression, returning the slope, intercept, and regression coefficients. Transforms between cartesian and polar co–ordinates are made using the built–in Matlab functions `cart2pol` and `pol2cart`.

```
for i1 = 1:size(E,1)  % step through the lines
  idvalid = find(~isnan(Z(i1,:)));  % find valid values (not NaN)
    % in plan view, convert to polar, with origin refposE,refposN
  [th,R]=cart2pol(E(i1,idvalid)-refposE(i1),N(i1,idvalid)-refposN(i1));
  flips = find(th<0);  % make R negative for negative angles
  R(flips) = -R(flips);
    % now find slope of R,Z (Z is always negative)
  [slp(i1),intrcpt(i1),r(i1),s(i1)] = ...
           find_slope(R,Z(i1,idvalid) - refposZ(i1));
end;
```

The series of line slopes and intercepts are then filtered. In this case, a 5th–order Butterworth filter has been used (built–in function `butter`) that has a width of 20 samples. The width will require adjustment according to the motions found in the data. The filter is applied using the built–in `filtfilt` command, which results in a forward–backward filter operation eliminating phase distortion of the results. Before filtering, a 20–sample–long pad is temporarily added to the start and end of each series to minimize end effects.

```
 % 5th order butterworth filter, with window 20 samples wide
[B,A] = butter(5,0.05);    % this may require tweeking
 % filter intercepts, filtfilt is a zero-lag filter
fintrcpt = filtfilt(B,A,... % pad start and end with mean values
    [ones(1,20)*mean(intrcpt) intrcpt ones(1,20)*mean(intrcpt)]);
fintrcpt = fintrcpt(21:end-20); % now remove padding
 % same for slopes
fslp = filtfilt(B,A,[ones(1,20)*mean(slp) slp ones(1,20)*mean(slp)]);
fslp = fslp(21:end-20);
```

Finally, the slope and intercept of each line are adjusted to the filtered values.

```
for i1 = 1:size(E,1) % step through lines
  idvalid = find(~isnan(Z(i1,:)));  % find valid values
    % in plan view, convert to polar, with origin refposE,refposN
  [th1,R]=cart2pol(E(i1,idvalid)-refposE(i1),N(i1,idvalid)-refposN(i1));
  flips = find(th1<0);  % make R negative for negative angles
  R(flips) = -R(flips);
    % convert to polar in a vertical plane, Z rel. to sonar head
  [th2,R2] = cart2pol(are,Z(i1,idvalid)-refposZ(i1));
    % then convert back after rotating to the filtered slope
  [R3,Znew(i1,idvalid)] = pol2cart(th2-(atan(slp(i1)-fslp(i1))),R2);
    % and calculate new E and N along original acrosstrack direction
  [Enew(i1,idvalid),Nnew(i1,idvalid)] = pol2cart(th1,abs(R3));
    % now make E and N relative to world coordinates again
  Enew(i1,idvalid) = Enew(i1,idvalid) + refposE(i1);
  Nnew(i1,idvalid) = Nnew(i1,idvalid) + refposN(i1);
    % adjust Z co-ordinate to filtered intercept, restore refposZ
  Znew(i1,idvalid) = Znew(i1,idvalid) + refposZ(i1) ...
                       - (intrcpt(i1)-fintrcpt(i1));
end;
```

The function `find_slope`:

```
function [slope,intercept,r,s] = find_slope(X,Z);
% calculate slope and intercept from linear least squares regression.
%    see CRC Math Handbook pgs 497-498 (27th Ed., 1985)
% input - X, Z = same-sized input vectors (your data)
% output - slope, intercept = of linear least sq. regression to your data
%          r,s = regression statistics (population correlation coeff
%                and standard error)
```

```
% trap improperly sized input
if (length(X) ~= length(Z)), error('Improper input vectors'); end;

N = length(X);
slope = (N*sum(X.*Z) - sum(X)*sum(Z))/(N*sum(X.^2) - sum(X)^2);
intercept = mean(Z) - slope*mean(X);
r = (N*sum(X.*Z) - sum(X)*sum(Z))/...
   sqrt((N*sum(X.^2) - sum(X)^2)*(N*sum(Z.^2) - sum(Z)^2));
s = sqrt(sum((Z - (intercept+slope*X)).^2)/(N-2));

return;
```

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(U) DRDC Atlantic recently acquired a Reson 8125 bathymetric sonar. This is a very high resolution multibeam sonar that requires accurate measurement of the instantaneous attitude and position of the vessel in order to properly determine seabed bathymetry. During early deployments of the instrument, roll and heave contamination of the bathymetric data resulted from less--than optimal configuration of the system ancillary sensors. In addition, the data show evidence of unresolved motions, mainly flex in the sonar mounting pole.

(U) In the absence of commercial software tools to deal with this problem, a method has been developed for removing some of these artifacts from the data. It is primarily intended for use in salvaging useful information from the early data sets now that the Reson system setup has subsequently been improved, however it is likely that pole flexure will continue to be an issue when deploying this sonar on CFAV Quest. The algorithm has been implemented in Matlab (The Mathworks, Inc.), and a student, David Cowan, has written a version for IDL (Research Systems, Inc.).

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